PETROGRAPHY AND PETROPHYSICAL CHARACTERIZATION OF CARBONATE ROCKS FROM GUNUNG RAPAT, PERAK, MALAYSIA

By

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11559

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

MAY 2012

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CERTIFICATION OF APPROVAL

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BACHELOR OF ENGINEERING (Hons)
(PETROLEUM ENGINEERING)

Approved by,

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(AP Dr Chow Weng Sum)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

May 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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(MUHAMMAD HAFIZ IZUDDIN BIN MAT DAIT)

ACKNOWLEDGEMENTS

It has been a great experience working on a subject such as carbonate rocks. I am grateful to my supervisor Associate Professor Dr Chow Weng Sum and my co-supervisor Mr Md Habibur Rahman for their guidance and sincere support all throughout the research. It has been a pleasure working in such a distinctive research with my supervisors who has contributed to oil and gas industry with important findings. The feeling of a great honor has always been effective for being privileged enough to study at the Universiti Teknologi PETRONAS (UTP). It is always a compliment to be thankful to all of the instructors at the faculty.

Special thanks also should be given Faculty of Geosciences and Petroleum Engineering, UTP for providing the laboratories equipments for this project. My family truly deserves appreciation as they have always been next to me. Their encouragement and support definitely increased the quality of the current study.

Finally the countless friends, technicians' staff of our faculty and the colleagues not mentioned deserves the best regards and appreciation for their invaluable contribution and support towards the realization of this study. Their support has been among one of the most important incentives to perform this work.

ABSTRACT

This project try to establish and investigate the correlations between rock physical properties (porosity, permeability and sonic velocity) of carbonates rocks from Gunung Rapat, Ipoh, Perak. Generally, correlations between rock physical properties of the carbonates are not easy to be established as compared to siliclastic sedimentary rocks due to the heterogeneity that they have in terms of pore type, grains and geometry. We used correlations of porosity-sonic velocity, permeability-sonic velocity and porosity-permeability in order to study the inter-relationship between the carbonate rocks physical properties. The preliminary results show a large scatter in the correlations of porosity-sonic velocity, permeability-sonic velocity and porosity-permeability thus indicates the heterogeneity of pore types, structure and distribution in the carbonates. From the SEM images, we found that the scattered correlations are may due to different kinds of microporosity and micrite microtextures presence in the carbonate rocks and also due to the variations in pore geometry. This study has a great significance in the process of a better understanding of how rock properties of carbonates relate to each other.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

List of Figures

List of Tables

NOMENCLATURES

XRD = X-ray Diffraction

DIA = Digital Image Analyzing

SEM = Scanning Electron Miscroscope

P-wave = Primary wave or Compressional wave

S-wave = Secondary wave or Shear wave

m/s = meter per second

mD = miliDarcy

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF STUDY

It is estimated that more than 60% of the world's oil and 40% of the world's gas reserves are held in carbonate reservoirs. The Middle East, for example, is dominated by carbonate fields, with around 70% of oil and 90% of gas reserves held within these reservoirs. Carbonate is a kind of sedimentary rock predominantly composed of calcite of organic, chemical or detrital origin [1]. Pore system of carbonate is very complex due to its biological origin and chemical reactivity. Carbonate rocks are usually more heterogeneous than clastic sedimentary rocks thus may contain different classes of porosity [2].

The porosity in a heterogeneous reservoir is composed of two main pore systems: primary porosity and secondary porosity. In the carbonate formations, the determination of the type and value of both primary and secondary porosity has a significance influence in giving the correct prediction of permeability and the evaluation of hydrocarbon reserves [3].

Eberli et al. (2003) classify pore types of carbonates into interparticle and intercrystalline porosity, microporosity, moldic porosity, intraframe porosity in frame/boundstone and low porosity carbonates [4]. The primary porosity is intergranular and intragranular porosity and while secondary porosity composed of fractures, vugs, moulds, and channels porosity. [5].

The correlations between porosity and other rock properties for carbonates are well-known, but they are too scattered and indicates the large uncertainties on the correlations.

Large scattering will result in large uncertainties in seismic inversion and porosity volumes calculations [6].

Studies and researches has been conducted a lot to find the relationship in the correlations between carbonate rock properties of carbonates but not in the Paleozoic carbonate at Gunung Rapat, Perak. This study intends to find such correlations of Paleozoic carbonate at Gunung Rapat, Perak.

1.2 PROBLEM STATEMENT

1.2.1 Problem Identification

Correlations between porosity and other rock properties of carbonates are not easy to be established due to the heterogeneity that they have in terms of pore type, grains and geometry. The complex pore systems and types create large scatter in the porosity and other rock properties relationships particularly in porosity-sonic velocity relationship. Furthermore, many studies have shown that sonic velocity and permeability of the carbonate depends not only on porosity distribution of the rocks, but the pore geometry as well [7]. However, currently, correlations and data on rock properties of carbonate rocks have been studied a lot and are documented but not in the Paleozoic carbonate in Gunung Rapat, Perak.

Theoretically, pore type gives uncertainties in porosity-velocity and porosity-permeability correlations and we expect the same thing for the carbonates at Gunung Rapat. In order to get more information on the rock properties of the carbonates, it is very important for us to quantify the correlations between porosity and other rock properties like sonic velocity and permeability.

The high diagenetic potential of carbonates results in intense alteration of the pore structure, which can lead to a decrease of effective porosity for flow and wave propagation. Permeability and elastic properties are strongly related to the rocks pore structure. As a result, samples of equal porosity can exhibit a wide variation of permeability and velocity [8].

For this project, we will try to establish the correlations of porosity and other rock properties and study whether the correlations will give the same uncertainties in like the current previous studies or not for the carbonates. The study on these correlations and relationships will give better understanding on the carbonates at Gunung Rapat.

1.2.2 Significance of The Project

Carbonates show often lack of correlation between porosity and other rock properties particularly with permeability and sonic velocity and the relationship between them are poorly understood. The development of carbonates rock physics model is also difficult because of its heterogeneity and complexity in the pore systems. Hence, this study has a great significance in the process of a getting better understanding on how rock properties of carbonates relate to each other.

1.3 OBJECTIVES

1. To establish correlations between rock physical properties (porosity and permeability), sonic velocity and sedimentological/diagenetic characteristic of carbonates from Gunung Rapat, Ipoh
2. To investigate the inverse yet scattered relationship between porosity and sonic velocity of the carbonates

3. To study the relationship between sonic velocity and permeability of the carbonates
4. To confirm the direct trend in the correlation of porosity and permeability
5. To investigate the factors affecting the amount porosity in the carbonates (dolomitization, grain size and distribution)

1.4 SCOPE OF STUDY

The scope of study for this project revolves around rock properties of the carbonates. The first stage of study (FYP 1) consists of researching for industry case studies to understand the theory behind carbonates formation and its digenesis processes. Other than that, understanding on the principal and origin of rock properties (porosity, permeability, sonic velocity) of the carbonates is also essential before moving to the second stage of study

In the second stage (FYP 2), the experiments will be carried out using Helium Porosimeter to quantify the amount of porosity while Mercury Porosimeter is used to determine the permeability. SEM and thin sections will be used to further analyze the porosity of the carbonates in terms of its crystallometry and and morphometry of micrite particles. Then, Sonic Viewer SX will be used to determine the sonic velocity of the carbonates. Lastly, XRD will be used to define the elements and minerals of the carbonates. Further evaluation will be done by analyzing the gathered results of rock properties of the carbonates. Then, a correlation between the porosity, permeability, sonic velocity and sedimentological/diagenetic characteristic will be quantified.

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1.5 THE RELEVANCY OF THE PROJECT

Despite the hydrocarbon they hold, carbonate rocks endure bad reputation for having either complicated interrelationship, or no relationship at all between porosity, permeability and sonic velocity thus can be very difficult to characterize them. Understanding the interrelationship that may exist is a challenge notably in determining the accurate ultimate hydrocarbon recovery. Better understanding will lead to better and advance carbonate reservoir characterization.

1.6 FEASIBILITY OF THE PROJECT

This project is fully experimental based. All equipments needed in order to achieve the objectives of the project are available in UTP. In the time given, the project could be done. This project can be done within seven months given that everything goes fine. The objectives can be achieved if the procedures are closely followed.

CHAPTER 2

LITERATURE REVIEW

2.1. CARBONATES FORMATION

Carbonate is a kind of sedimentary rock consisting mainly of the mineral calcite (calcium carbonate, $CaCO_3$) [7]. Common impurities in carbonates include chert (microcrystalline, cryptocrystalline quartz or amorphous silica, SiO_2, clay, organic matter and iron oxides [9]. Carbonates deposit often comprise the aquifers from which we get water, act as stratigraphic reservoirs for oil and gas deposits, and are widely used as industrial minerals. Some carbonates are formed almost entirely of skeletons of marine organisms and form very distinctive fossiliferous rocks [10].

Siliclastic sedimentary rocks were formed through erosion and transportation of material from existing rocks, while carbonates formed through biological activity and inorganic precipitation. Due to its biological origin, carbonates deposits restrict their occurrences to places with specific temperatures and other life-sustaining condition. The constant evolution of the carbonate-producing organisms adds complexity to the carbonates' studies. The mineralogy of the carbonates is simple – it constitutes of calcite ($CaCo_3$), dolomite ($CaMg(CO_3)_2$) and evaporite minerals such as anhydrite ($CaSo_4$) and gypsum ($CaSo_4.2H_2O$) predominant, and has clay then siliclastic sedimentary rocks [11]. Even though mineralogy of limestone is quite simple, the composition is high in variations. Six main components can be recognized in limestone – grains, carbonate mud sediment (matrix between grains), terrigenous components, sparry calcite, replacive crystals of dolomites/evaporate of minerals/other non-carbonates and pore space [12].

A variety of properties are available to classify the limestone such as color, grains, crystal size, composition and texture/fabric. However, the widely used classifications are based on the concept of textural (fabric) maturity, where the fabric is believed to relate to the energy level during the deposition of the limestone. This is the basis of the classifications proposed by Folk (1959, 1962), Dunham (1962), Leighton and Pendexter (1962), Bissel and Chilingar (1967) and Fuchtbauer (1974). The most widely used are Folk (1959, 1962) and Dunham (1962) type of classifications [13].

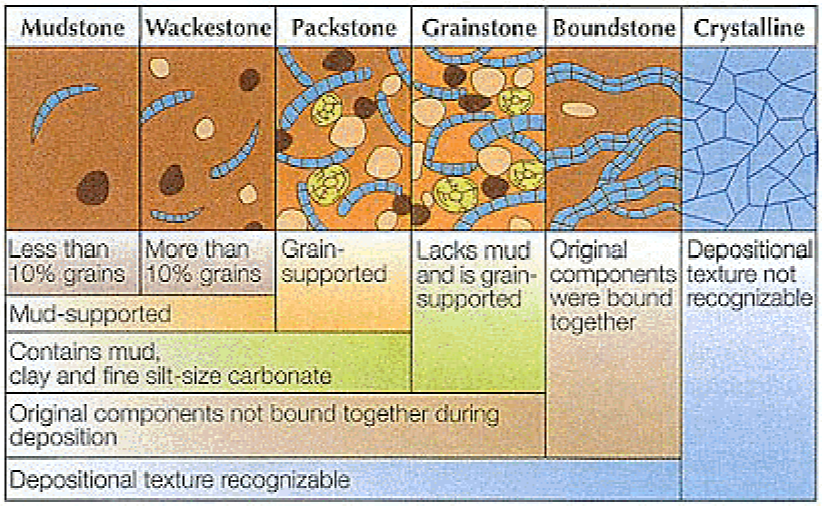


Figure 1. *Dunham's classification of carbonate rocks*

2.2. POROSITY OF CARBONATES

Porosity is the percentage of a rock or sedimentary deposit that consists of voids and open space. Porosity of a rock is a measure of its ability to hold a fluid. Porosity in carbonate is interesting as it is important in hydrocarbon exploration. Nevertheless, porosity in carbonate is a bit different from sandstone. It is irregular in types and has low percentage in distribution compared to sandstone reservoirs. Most of carbonate and limestone reservoirs have porosity as low as 5-10% only [13].

Petrophysicists and geologist have made several types of porosity classifications to characterize carbonate reservoirs. Some of the classifications are developed by Choquette and Pray, Archie, Lucia and Lonoy. The classification developed by Choquette and Pray is linked to sedimentological fabric. Pore system classifications by Archie and Lucia are preferred with respect to integration but difficult to incorporate them into sedimentological modeling. They are also difficult to use in exploration. Lonoy recently proposed a new pore-system classification based on pore type, thin section analysis and porosity-permeability relations [2].

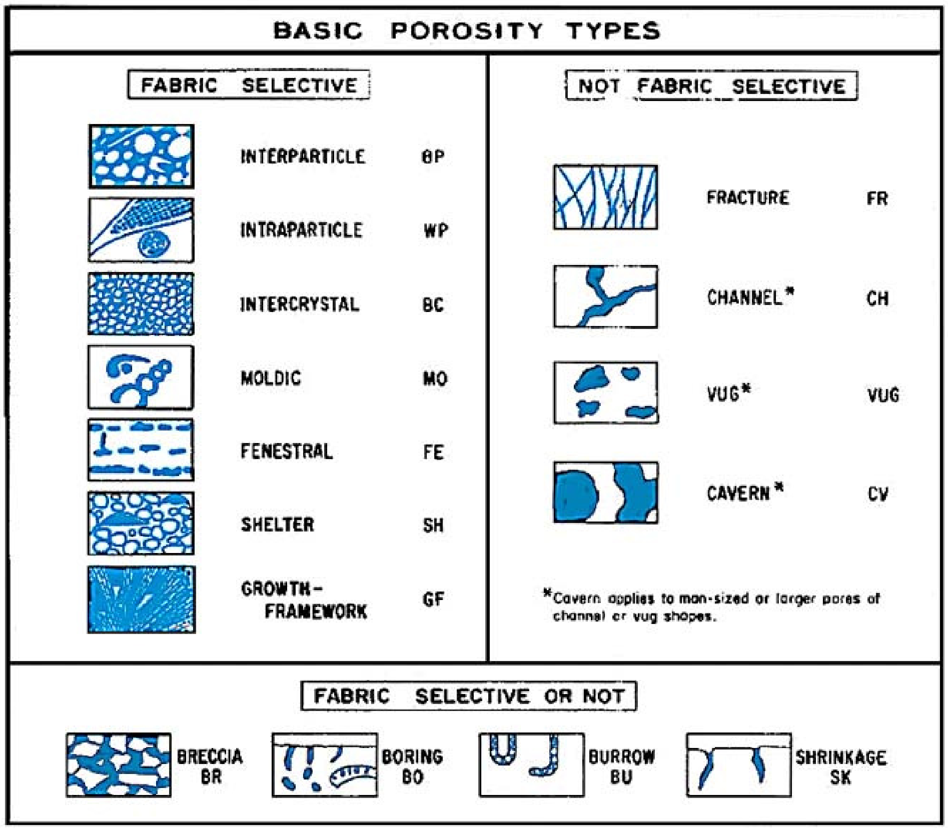


Figure 2. *Choquette and Pray's classification of porosity of carbonate rocks*

Carbonate reservoirs give challenges to the engineers as they have tendency to be very tight and heterogeneous due to depositional and diagenesis processes [14]. Heterogeneous carbonate reservoirs mean that several type of porosity coexist simultaneously in the porosity system of the reservoirs themselves. Those are primary porosity (intergranular / intragranular) and secondary porosity (fractures, vugs, moulds, and channels) [5]. In general, carbonate porosity is divided into primary and secondary porosity. These different types of porosity are not easily distinguishable unless the primary pores and the diagenesis processes that occurred are studied [15]. The originally homogeneous matrix may turn heterogeneous due to karstification and/or aggradation.

Carbonate reservoirs are thus intensely heterogeneous with vugs, moulds, fractures and cementations randomly distributed within a homogeneous porous matrix [16].

The term ‘primary porosity’ is given to the pore spaces which were formed during the final sedimentation or formation of the rock. Primary porosity is formed in two basic stages, the predepositional stage and the depositional stage. The predepositional stage begins when individual sedimentary particles form and includes intragranular porosity such as is seen in forams, pellets, ooids, and other non-skeletal grains. This type of porosity can be very important in certain sediments. The depositional stage is the time involved in final deposition, at the site of final burial of sediment or a growing organic framework. Porosity formed during this stage is termed depositional porosity and is important relative to the total volume of carbonate porosity observed in carbonate rocks and sediments (Choquette and Pray, 1970) [17]. .

The ‘secondary porosity’ on the other hand is developed at any time after final deposition. The time involved in the generation of secondary porosity relative to primary porosity may be enormous. This time interval may be divided into stages based on differences in the porosity-modifying processes occurring in shallow surficial diagenetic environments versus those encountered during deep burial. Choquette and Pray (1970) recognized three stages: eogenetic, telogenetic, and mesogenetic [17]. The secondary porosity is subdivided into three groups based on the most dominant geological process: solution porosity, dolomitization, fracture porosity caused by tectonic activities such as folding and faulting [5].

The correct evaluation for carbonate rocks and reservoirs which are having double porosity needed to be done separately in order to quantify their primary and secondary porosity. Type, distribution and porosity value of secondary pore system (fractures, vugs, moulds, and channels) give major influence in determining the saturation, permeability and hydrocarbon reserves [18]. The determination of secondary porosity type and separate estimation of the value of both primary and secondary porosity is necessary for correct and good permeability prediction, reserve evaluation and adequate exploitation of carbonate reservoirs [19]. During depositional and diagenesis processes, primary porosity of the carbonate may be improved by the enlargement of the pore spaces, or may be destroyed by filling the pore spaces with the secondary chemical deposits [20].

2.3. SONIC VELOCITY OF CARBONATES

Acoustic or sonic velocity is define as the rate at which wave travels through a medium (a scalar) or the rate at which body is displaced in a given direction (a vector), commonly symbolized by v. In geophysics, velocity is a property of a medium-distance divide by travel time. Sonic velocity can be determined from laboratory measurements, acoustic and sonic logs, vertical seismic profiles or from seismic data.

The analysis of the sonic velocity of the waves can be used for hydrocarbon exploration, well log analysis, abnormal pressure detection, fracture detection and determination of stress orientation, characterization of permafrost, geothermal exploration, porosity mapping in hydrocarbon reservoirs, temperature mapping, monitoring EOR processes and tracking flow fronts, monitoring gas cap movement, monitoring water flooding and determination of reservoir heterogeneity and permeability anisotropy [21].

The tool used in measurement of sonic velocity measures the time it takes for elastic wave to travel from the transmitter to the receiver. When the sound/elastic waves transmitted by the transmitter and travels through the rocks, it travels in various forms while undergoing dispersion (spreading of the wave energy in time and space) and attenuation (loss of energy through absorption of energy by the formations). When the elastic waves arrive at the receiver after going through the rocks, it arrives in different times in the form of different type of waves. This is because the different types of wave travel with different velocities in the rock or take different pathways to the receiver. After some time, the first wave that arrive with fastest velocity is the compressional or longitudinal or pressure wave (P-wave). It has small amplitude. After that, the transverse or shear waves (S-wave). It is slower than P-wave but have bigger amplitude. The shear wave cannot propagate in fluids, as fluids do not behave elastically under shear deformation. Then other type of waves arrives such as Rayleigh waves, Stoneley waves and mud waves. The first two (P-wave and S-wave) are the most important types [22]. Interpretation of the velocity of P-wave (Vp) and S-wave (Vs) can be used to determine the rock properties like porosity, lithology, gas detection, rick strength, synthetic seismic, seismic correlation, and geopressure prediction [23].

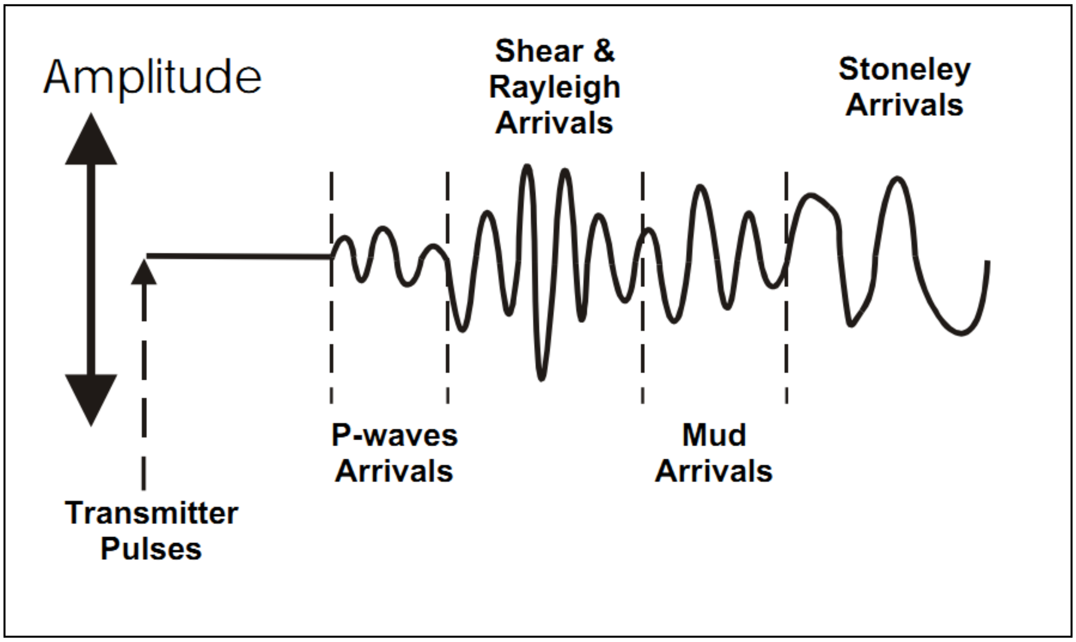


Figure 3. The geophysical wavetrain received by a sonic log

However, in carbonates, it is difficult to find the direct relationship among sonic velocity and rock properties (such as permeability and porosity) due to the rapid and pervasive diagenetic alterations that change the mineralogy and pore structure within carbonate. As example, Ebeli et. al (2003) reported that there is wide range of sonic velocity in carbonates, where the range for P-wave velocity, Vp is from 1700 to 6600 m/s and from 600 to 3500 m/s for S-wave velocity, Vs [4]. Thus, to develop a carbonate's rock physics and properties is harder compared to clastic rocks. The reason is because the fundamental differences between carbonate and clastic rocks. Clastic rocks, which are predominantly sandstone, can have a wide range of reservoir quality through variations in mineralogy, grain size d … ırbonate rocks on the other side show a wide range of reservoir quality through pore size distribution, pore connectivity, brittleness and fracturing, then the degree of dolomitization. In short, clastic rocks reservoir quality is governed by mineralogy and texture while carbonate rocks reservoir is governed by pore structure. Usually, traditional petrophysics practices the utilization of mineralogical criteria, so they are notionally tuned to clastic rocks. So, petrophysical correlations for carbonate rocks are not straight forward and have more uncertainties [24].

As example, porosity is one of the main rock properties that affect the sonic velocities in most of the rocks. But, for carbonate rocks, it is not that simple. The way the pore spaces formed and their type of porosity affect the sonic velocity [4]. Eberli et al (2003) suggested that there is strong relation between pore types and sonic velocity. They found that even with the rocks that have the same amount of porosity, the sonic velocity is differs widely. This is because not only the porosity affect the sonic velocity, the pore types also give quite effect as well (Figure 4). They classify the pore types into five categories which are – interparticle and intercrystalline porosity, microporosity, moldic porosity, intraframe porosity in frame/boundstone and low porosity carbonates [4].

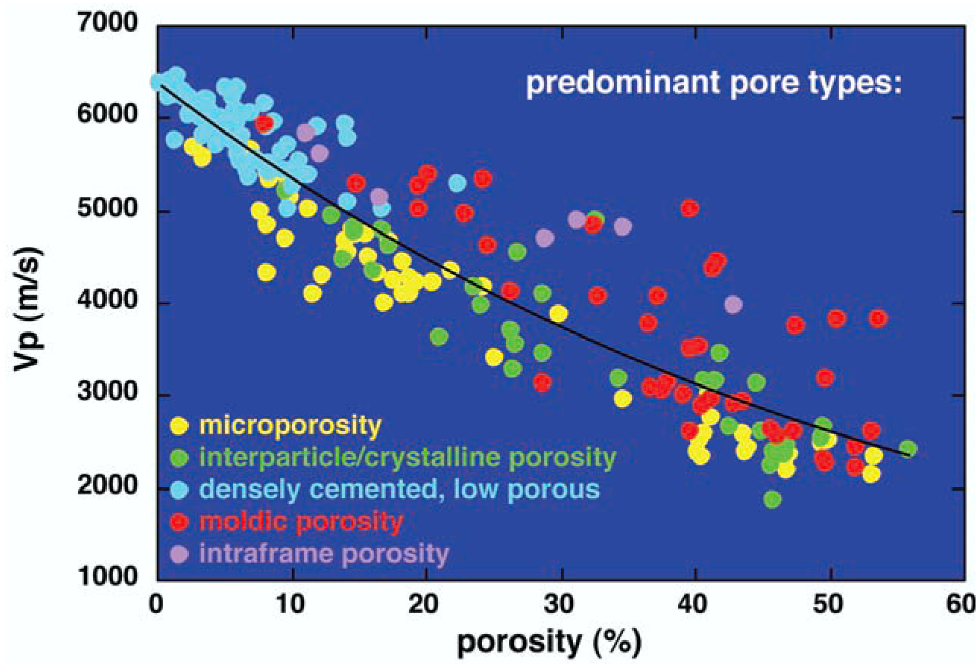


Figure 4. *Graph of velocity (at 8 MPa effective pressure) versus porosity of various pore types of carbonates with an exponential best fit curve through the data for reference. Different pore types cluster in the porosity velocity field, indicating that scattering at equal porosity is caused by the specific pore type and their resultant elastic property*

Weger et. al (2004) reported that a there is very large scattered in correlation between sonic velocity and porosity due to different pore structures from 123 carbonate samples. Porosity values vary from 5% to over 40%, with velocities ranging from 3000 m/s to over 6500 m/s [25]. Baechle et. al (2008) also discover the same trend from the oomoldic carbonate samples. In the dataset, the pore population is dominated by oomoldic pore types and consists of spherical pores, with porosities ranging from 5-35%. These oomoldic carbonate rocks are having velocity from the range of 320 m/s to 6500 m/s. The correlation between sonic velocity and porosity is largely scattered with up to 2000m/s difference at a given porosity for the same oomoldic macro-pore type [26]. While Kumar and Han (2005) reported that even though velocity-porosity relationship in carbonate reservoirs shows inverse relationship, the measured velocities show lot of scattering in the trend [27].

2.4 PERMEABILITY OF CARBONATES

The petrophysical properties of reservoir formations containing hydrocarbons dictate the quantities of fluids trapped within their pore space. The ability of these fluids to flow through rocks together with the ability of rocks to transmit fluids via the interconnected pores is called permeability. Permeability is considered one of the most important petrophysical rock properties as it is essential to estimate flow rates and fluid recovery [28]. Permeability prediction in carbonates requires a different model than that used for clastics. Clastics are more aptly described using Carmen-Kozeny surface-area models because diagenesis causes an alteration of the pore space by surface coating clays/minerals. Carbonates however are better described using pore throat sizes, their variations in size and their interconnection. Large, well sorted pore throats with good interconnection will result in high permeability; small, poorly sorted pore throats with poor interconnection will result in reduced permeability. Dziuba (1996) describe three variables that dominate permeability in carbonates - pore throat radius, connectivity and geometrical factors [29].

Most experimental studies conducted in laboratories to understand rock properties have been carried out on sandstones. However, applying the relationships developed for sandstones to carbonate rocks is challenging as it works in only some cases and it does not work in others. From the engineering point of view, rock heterogeneity, which is common in carbonate reservoirs, makes it difficult to obtain representative permeability of the reservoir formation far away from the wellbore [29]. The complex pore structure of carbonate rocks is mainly a consequence of diagenetic post-depositional processes, such as compaction, dissolution, dolomitization, and cementation. Such processes play a fundamental role in the porosity and microfabric evolution, enhancing or reducing the pore space. These complexities make it difficult to understand the relationships of sonic velocity and permeability for carbonate rocks. [30].

Md Habibur Rahman et. al (2011) reported that an inverse yet non-linear relationship between permeability and sonic velocity. They also reported a non-linear and scattered correlation between permeability and porosity. They suggested deducting microporosity from total porosity to have better correlations on permeability-porosity relationship [31].

CHAPTER 3

METHODOLOGY

3.1 RESEARCH FLOW

Figure 5 below describes the overall methodology and general flow of this project.

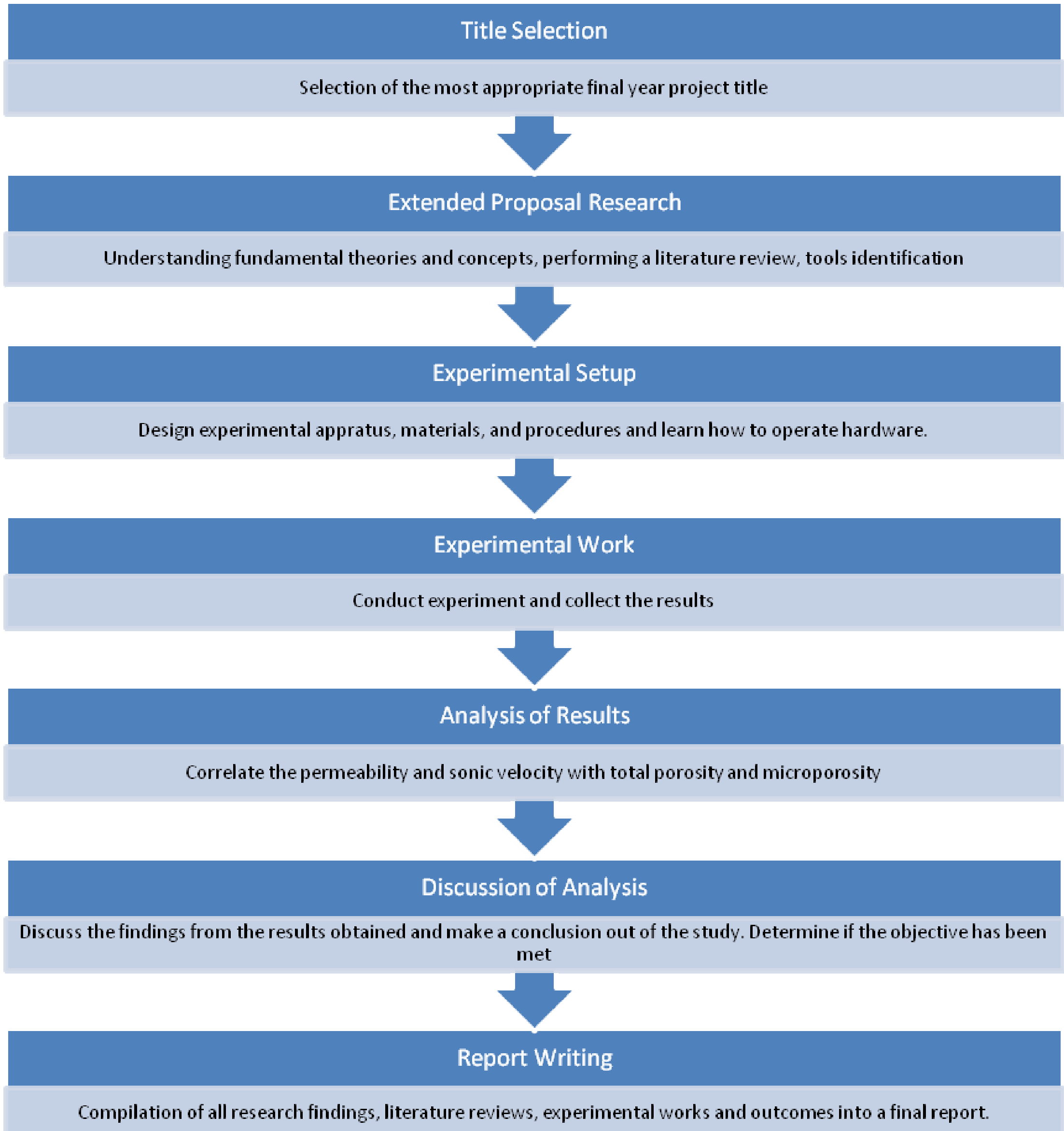


Figure 5. *Flowchart representation of Project Methodology*

3.2 METHODOLOGY

Several procedures need to be conducted for this project in order to get the expected results. They are case study, drill for the core plugs, laboratory experiments and data analysis.

3.2.1 Case Study

For the first procedure, technical papers, books, journals and related articles need to be studied. Same studies on relationship between porosity and other rock properties of carbonate rocks done by other researchers will be taken as the main references

3.2.2 Drill for the Core Plugs

For this study, 20 carbonate core plug samples from outcrop rocks of Gunung Rapat which are 1 inch in diameter and 1.5 inch long are obtained for analysis. The 20 core plugs are taken from different area of Gunung Rapat in order to get variations in terms of rock types and properties.

3.2.3 Laboratory Experiments

Several laboratory experiments will be conducted to quantify the amount of porosity and other rock properties of the carbonates.

3.2.3.1 Quantification of Type of Rocks and Porosity

In this study, 1 thin section from each on the 20 carbonate core plugs will be prepared. On average 20 thin section images will be taken using Olympus BX 51 microscope and analyzed using 'Analysis' software – DIA analysis software. From the thin section images, the type of the rock and porosity will be identified. Dunham's (1962) type of classification for carbonates will be used to define the type of the carbonates for the core plugs. The type of porosity on the other hand will be determined by using porosity classification scheme of Choquette and Pray.

By using thin section images and analysis using Dunham's type of classification for carbonates, Choquette and Pray's as well as SEM, we can get the characteristics of the carbonates' porosity. We can understand the origin and nature of the porosity, the types as well as factors affecting the distribution of pore spaces in the carbonates.

For the value of porosity in the carbonates, Helium Porosimeter instrument developed by Vinci Technologies will be used. The reason why we used helium gas is because to prevent any effects on carbonates if we use water (carbonate and carbonate can dissolved in water). For the use of gas, Klikenberg corrected measurement is considered due to gas slippage effect.

3.2.3.2 Quantification of Sonic Velocity

The 20 core plug samples will be analyzed using Sonic Viewer SX instrument developed by OYO to quantify the sonic velocity and acoustic properties of the carbonates. From this sonic velocity, P-wave and S-wave will be taken into analysis.

3.2.3.3 Quantification of Permeability

Permeability of the carbonates will be quantified using Porosimeter Pascal 140 and 240 developed by Thermo Scientific. This porosimeter uses mercury injection to give the result of porosity and permeability. The reason mercury is used instead of gas to get the permeability is because of some of the pore spaces are too small and gas could not access into it.

3.2.3.4 Quantification of the Elements and Minerals

XRD will be used to compute the elements and minerals of the carbonates. The types of elements and their composition will determine whether the carbonate is limestone or dolomite. Mineral composition in the rocks also might influence the porosity distribution.

3.2.3.5 Study of Morphology of Micrite Particles

Lastly, after examining the relations that porosity has with other rock properties, we will study the thin section images as well as photomicrographs from SEM to see the factors that might affect the porosity distribution (such as size and geometry of grain, cement and matrix) and the effects they have on rock properties (porosity, permeability and sonic velocity).

3.2.4 Data Analysis

Rock properties (porosity, sonic velocity and permeability) determined from the laboratory experiments will be analyzed to study the relationship they have with each other. Then we will try to make several correlations in order to quantify the relationships. The correlations which we are going to plot are:

1) Porosity - P-wave
2) Porosity – S-wave
3) Porosity – permeability
4) Permeability – P-wave
5) Permeability – S-wave

3.3 PROJECT ACTIVITIES

Table 1 – Project activities planned for Final Year Project

Activities	*Starting Month*	*Finishing Month*
Survey on the availability of suggested Experiment Apparatus	1st November 2011	4th November 2011
Study on method to obtain porosity from core plug samples and how to quantify them	5th November 2011	14th November 2011
Study on theories of porosity, permeability and sonic velocity of the core plug samples	15th November 2011	28th November 2011
Field trip to Gunung Rapat for obtaining the core plug samples	29th November 2011	11st December 2011
Thin sections preparation	12nd December 2011	21st December 2011
Experiment on core plug samples to quantify the amount of porosity	22nd December 2011	31st December 2011
Experiment on core plug samples to quantify the amount of sonic velocity	1st January 2012	15th January 2012
Experiment on core plug samples to quantify the amount of permeability	16th January 2012	31st January 2012
Experiment on samples to get type of minerals and their detail image by using XRD and SEM	1st February 2012	15th February 2012
Analysis of the data	16^{h} February 2012	2nd March 2012
Report documentation	3rd March 2012	30th April 2012

3.4 GANTT CHART & KEY MILESTONES

Table 2 – Gantt chart and Key Milestone through the Final Year Project

	1ST SEM				2ND SEM				
Activity	S	O	N	D	J	F	M	A	M
Selection of Project Topic	■	■							
Preliminary Research Work		■							
Submission of Extended Proposal Defense			■						
Survey on the availability of suggested Experiment Apparatus			■						
Purchase unavailability things. Study on how to prepare the solutions.			■						
Proposal defense. Present details on methodology of the experiment.			■						
Core plugs preparations from Gunung Rapat, Perak.				■					
Submission of Interim Draft Report				■					
Submission of Interim Report				■					
Thin sections preparations and experiment on core plug samples to determine the minerals of the carbonates using XRD					■				
Experiment on core plug samples to quantify the amount of porosity and sonic velocity					■	■			
Experiment on core plug samples to quantify the amount of permeability					■	■			
Experiment on samples to get the detail images by using SEM						■	■		
Analysis of the data						■	■		
Submission of progress report							■		
Submission of poster								■	
Submission of technical paper								■	
Submission of final report (softbound)								■	
Final presentation / viva								■	
Submission of final report (hardbound)									■

3.5 TOOLS

In this project, core plug samples are the major tool used. Equipments such as Helium Porosimeter, Sonic Viewer SX, Mercury Porosimeter Pascal 140 and 240, X-ray Diffraction (XRD) and Scanning Electron Microscope (SEM) can be obtained from laboratories.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 THE CORRELATIONS

Using X-ray Diffraction (XRD), we differentiate our carbonate samples between limestone and dolomites. Our mineral of interest is the presence of Magnesium (Mg) which indicates the dolomite characteristic of the rocks. XRD results show that the dolomite is presence in the carbonate rocks from Gunung Rapat (Figure 6). We also tested the samples using dilute 3 molar hydrochloric acid (3 M HCl) for the confirmation of the presence of the dolomite in our samples. A few drops of the HCL are put on the samples, and limestone responds by fizzing vigorously while dolomite fizzes only very slowly.

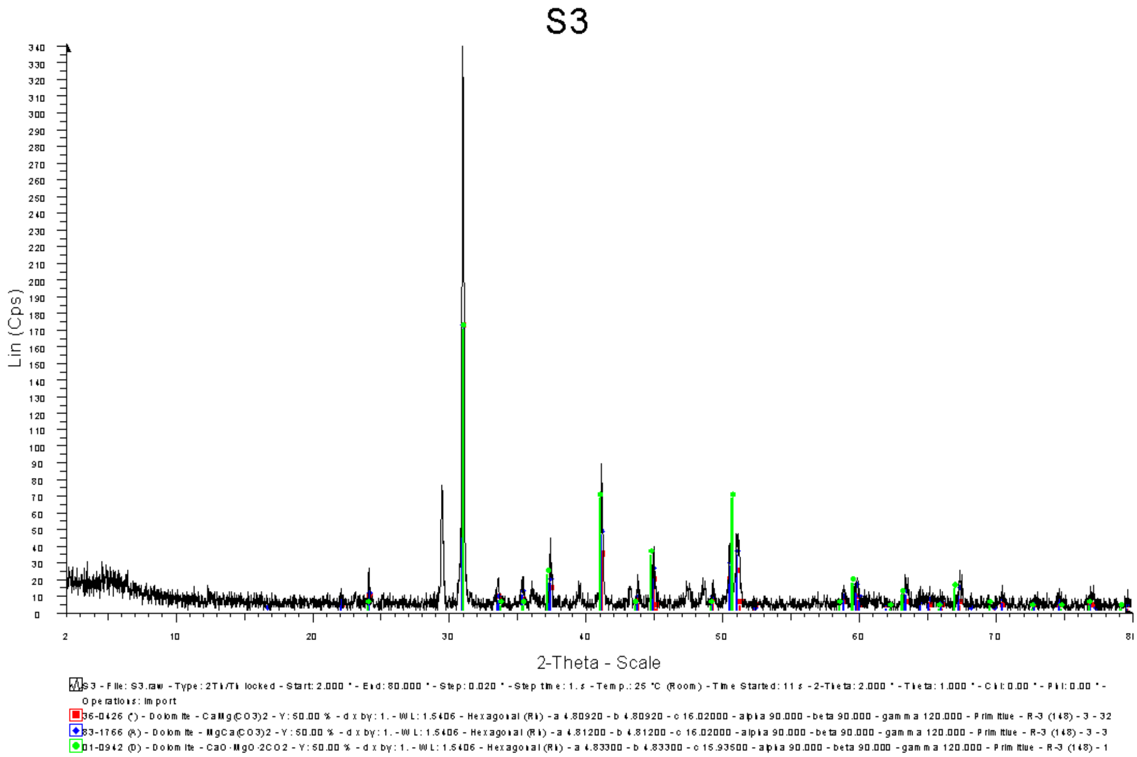


Figure 6. *Example of XRD result that determines the dolomite type*

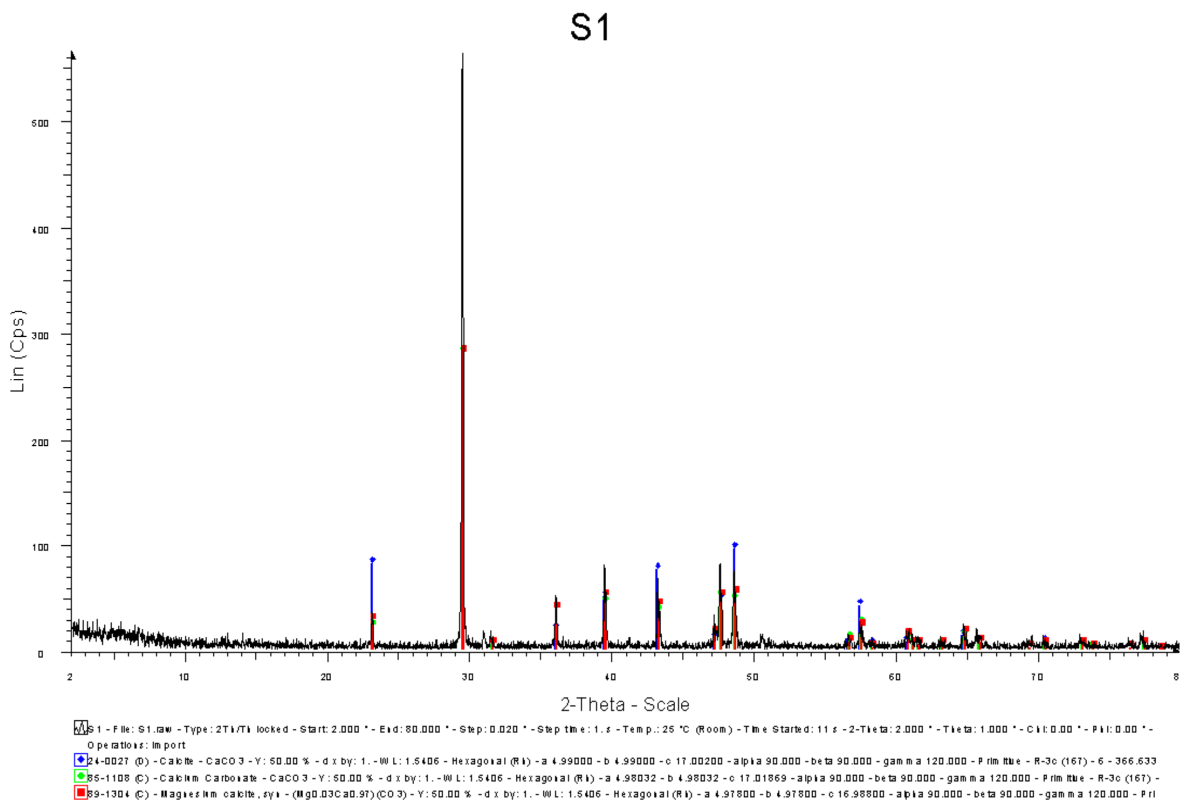


Figure 7. *Example of XRD result that determines the limestone type*

The P-wave velocity for our studied samples ranges from 4964 m/s to 6818 m/s and for S-wave velocity's range on the other hand is from 2014 m/s to 4258 m/s. Porosity amount for our samples are ranging from 1.6% to 6.1%. Permeability ranges from 0.000135 mD to 0.610234 mD.

When we try to plot and establish the correlation and relationship between porosity and sonic velocity (P-wave and S-wave velocity), we observe a scattered and wide trends on those correlations (Figure 8 and Figure 9). The correlations of porosity-P-wave velocity and porosity-S-wave velocity shows inverse relationships where when the amount or percentage of the porosity increases, the value of both P-wave and S-wave velocity will decrease. This inverse trend is predictable because the amount and distribution of the pore spaces inside the samples directly affect the sonic velocity. Theoretically, the more pore spaces inside the rocks, the more tortuous the sound path will be thus the longer it takes for the sound to travel through the rocks from the transmitter to the receiver. As for the rocks which are denser and have less pore spaces, the sound will travel faster through them. The sound travels faster through solid material compared to pore spaces. As a result, the rocks with higher porosity (has lower pore spaces) tends to have slower sonic velocity and vice versa.

However, we still can observe large scatter which indicates uncertainties in the correlations (Figure 8 and Figure 9). The large scatter in the correlations is due to the heterogeneity they have in pore type, pore shape and geometry. The heterogeneity on the rocks is related to pore structure Eberli et al. (2003) [4].

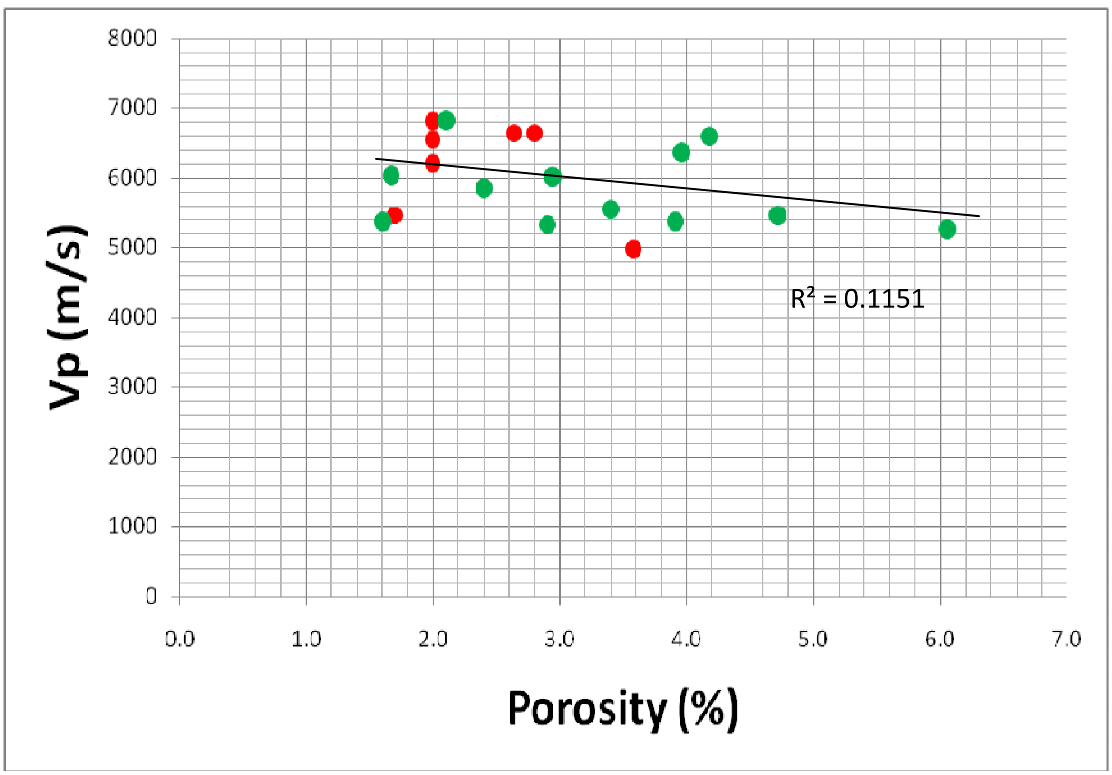
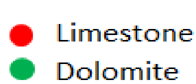


Figure 8*.Graph of P-wave velocity versus porosity*

Legends:



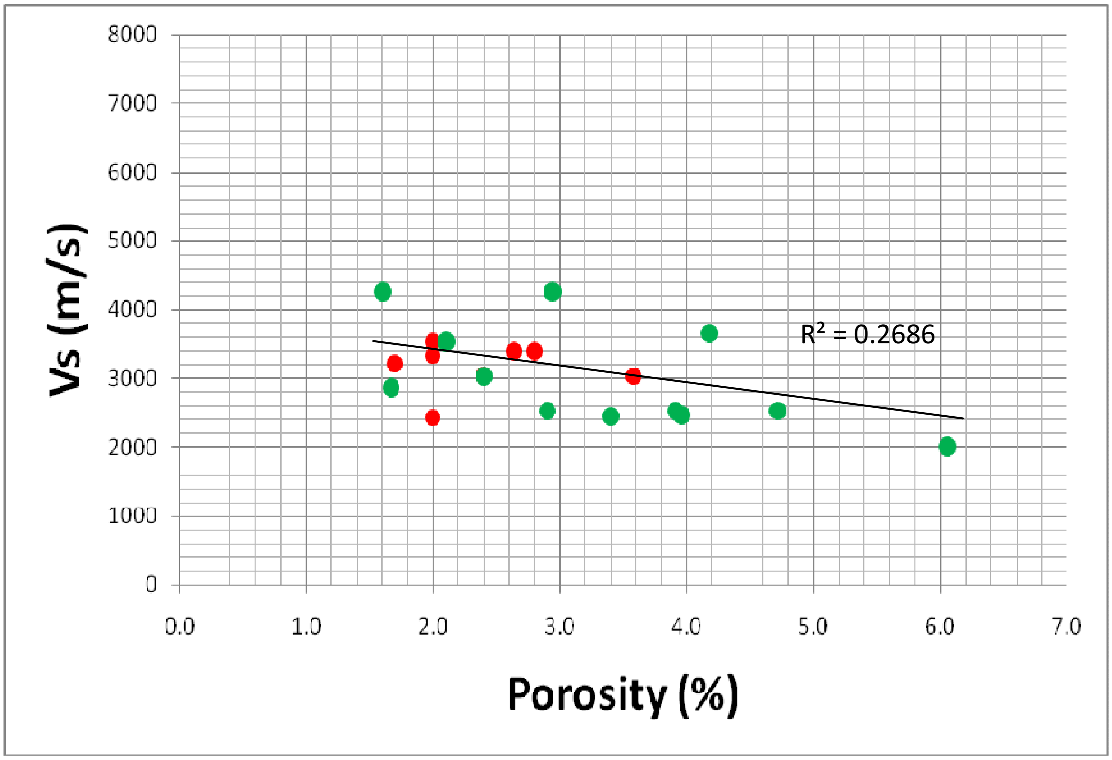


Figure 9. *Graph of S-wave velocity versus porosity*

There is a significance difference between sonic porosity at comparable porosity, which is up to 1200 m/s. As example, the samples that have porosity of approximately 3%, the range of P-wave velocity is from 5314 m/s to 6636 m/s (Figure 8). Another significance difference is from porosity less than 4%. The difference between 3.6% porosity, which has lowest value of P-wave velocity (4964 m/s) and 2.0% porosity, which has the highest value (6818 ms/) is quite large - 1854 m/s. These observations show that there is significance degree of heterogeneity for carbonate rocks in Gunung Rapat with the same or very similar amount of porosity. Similar observation on these poor correlations where similar porosity value has wide variations of sonic velocity values also reported by Eberli et al. (2003) and Wang et al. (1991). The study by Eberli et al. (2003) found that velocity differences at porosity less than 10% can be around 2000 m/s [4]. Wang et al. (1991) on the other hand found that poor linear correlation between porosity and sonic velocity with correlations factors ranging from 0.67 for fry rocks to 0.81 for saturated rocks. They suggested that other than the amount of porosity, the other intrinsic properties of the rocks like pore geometry and mineral composition also affect the sonic velocity [32].

We also observe that the porosity can vary at similar sonic velocity (Figure 8). As example, the samples with P-wave velocity ranges from 5247 m/s to 6033 m/s can have porosity amount anywhere between 1.7% to 6.1%. The characteristic of carbonate sediments that are prone to rapid and pervasive digenetic alterations such as continuous cementation and dissolution processes changes the mineralogy and pore structure of the rocks. All these modifications change the sonic velocity of the rocks thus resulting in a dynamic relationship between porosity and sonic velocity [4]. Baechle et al. (2004) also observed similar finding. The P-wave velocity ranges from 5000 m/s to 6000 m/s have wide variations of porosity from 3% to 26%. They suggested the separation of porosity into macroporosity and microporosity in order to have better correlation in porosity-sonic velocity relationship [33]. Md Habibur Rahman et. al (2011) suggested that the sonic velocity of a carbonate reservoir rock is lower when the proportion of microporosity is higher [31].

The correlations of permeability-sonic velocity also show the similar inverse trend like the correlations of porosity-sonic velocity in their relationship (Figure 10 and Figure 11). However, the permeability-sonic velocity correlations are more scattered and poorer. This is because, right now, not only pore type, shape and geometry that influence the porosity-sonic velocity relationship of the rocks, permeability is also affected by pore connectivity, channels and fractures. These result in wider scattered correlations compared to porosity-sonic velocity correlations. In some cases, permeability properties of carbonate rocks are enhanced by the process of diagenesis like dissolution which creates channels. Once the channels were created, the amount of fluid flow through the rocks will increase therefore improve permeability. Fracture also increases the permeability of the rocks especially when it is parallel to the flow direction. Fracture can connect the isolated pore space thus enable them as a medium for flow of the fluid. Fracture porosity in this case is called secondary porosity. In exceedingly rare cases, non-reservoir rocks such as granite can become reservoir rocks if sufficient fracturing occurs. These features increase the degree of uncertainty in porosity-sonic velocity and permeability-sonic velocity relationships thus make their correlations very complicated. The additional factors that affecting the permeability that creates more complicated relationship for permeability-sonic velocity correlations is expected and indicate the weaker relationship it has compared to porosity-sonic velocity correlations.

We also found that sonic velocity has wide variations at similar permeability (Figure 10). The difference value is quite significance – some of the cases the difference is more than 1500 m/s. For instance, at permeability of 0.2 mD and 0.3 mD, the P-wave velocity ranges from 4964 m/s to 6636 m/s with difference of 1672 m/s. Equally, permeability also has wide variations at similar sonic velocity. As example, samples that have P-wave velocity between 5247 m/s to 5364 m/s can have permeability anywhere between 0.10567 mD to 0.6102 mD.

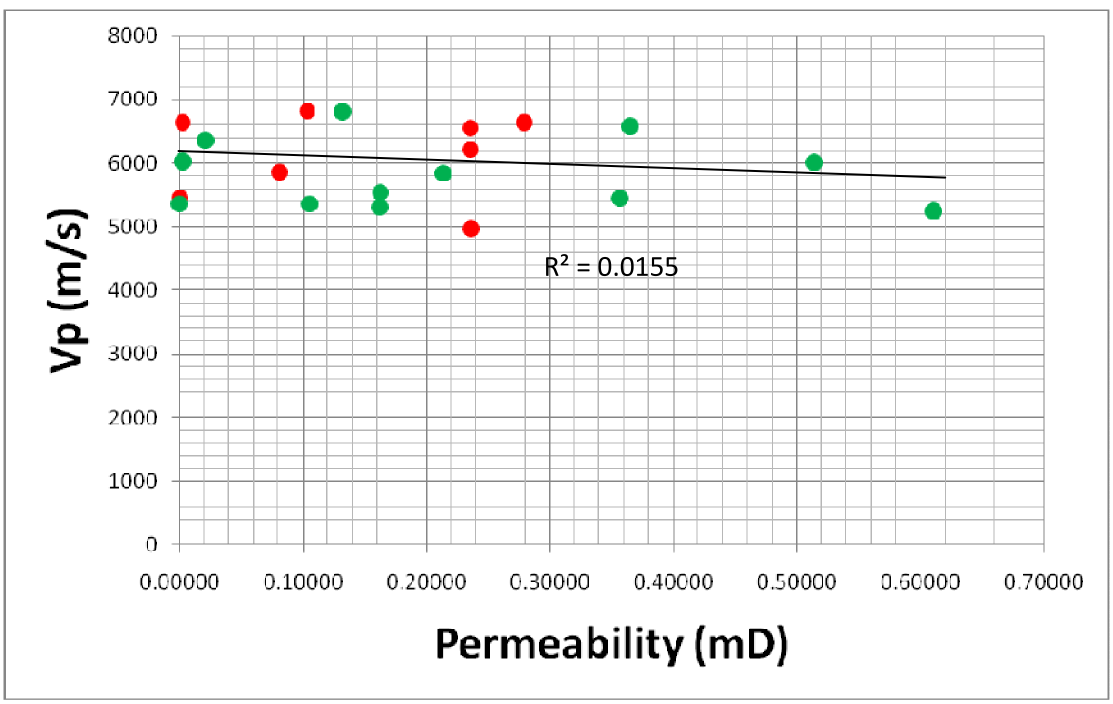


Figure 10. *Graph of P-wave velocity versus permeability*

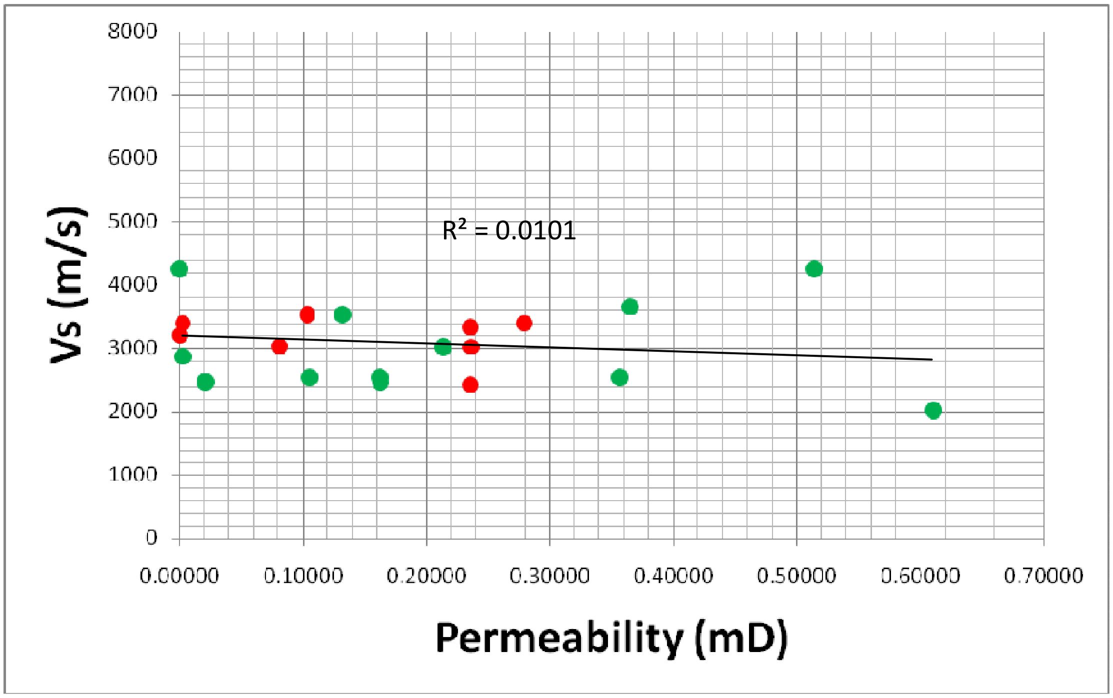


Figure 11. *Graph of S-wave velocity versus permeability*

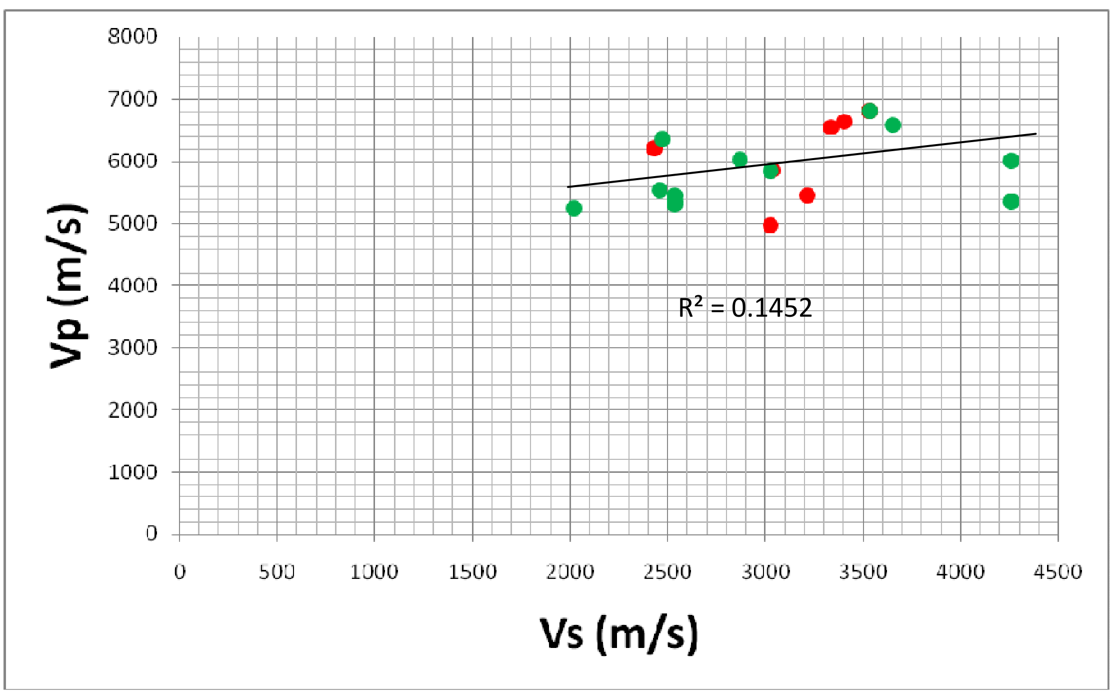


Figure 12. *Graph of P-wave velocity versus S-wave velocity*

For the relationship between porosity and permeability, we observe the direct and linear trend between these two properties (Figure 13). Low porosity value will give low permeability value and vice versa. This is expected result as the more pore spaces that a rock has; the more it has a chance of transmitting the fluid. Nevertheless, permeability also depends on connectivity of the pore spaces. There are some extremely rare cases where a reservoir has high amount of porosity but has low permeability because of the high abundance of isolated (not-connected) porosity constituted in the rock. However, the correlations that we get here is quite scatter even though the general direct trend still can be seen. This is because the heterogeneity of the carbonates affects the relationship. Similar observation also recorded by Eberli et al. (2004). They found a large scatter in the porosity-permeability correlations which indicates high uncertainties. They suggested that the large scatter is occurred due to the presence of "in-effective" microporosity [34]. The high diagenetic potential of carbonate results in intense alteration of the pore structure, which can lead to decrease of effective porosity for flow and wave propagation.

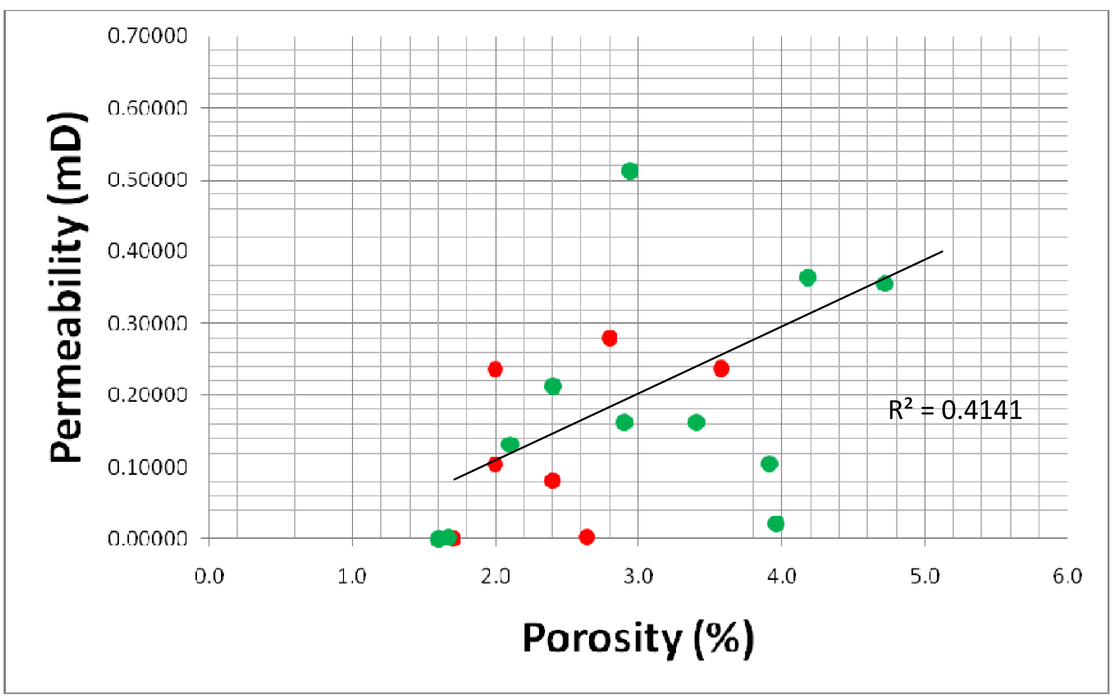


Figure 13. *Graph of permeability versus porosity*

4.2 THIN SECTION IMAGES

From our thin section images, we use Dunham (1962)'s classification of carbonate rocks. We use this type of classification because not only is it easy to apply but it also accurately communicates textural data and ideas that have genetic significance. The classification is based on depositional texture and defines carbonate rocks depending on whether they are grain-supported or matrix supported, on the dominant type of grain (allochem), and whether their matrix is dominated by micrite or sparry calcite. Types include mudstone, wackestone, packstone, grainstone, boundstone and crystalline carbonate. The Dunham classification system is most useful for microfacies interpretation of the environment of deposition of carbonates. An alternative classification system is the Folk classification [35].

So, for our 20 carbonates samples, we found 3 types of carbonate rocks which are packestone, grainstone and crystalline dolomite. Packestone is supported by grains but also containing some calcareous mud (Figure 14 and Figure 15). Grainstone is grain-supported and mud-free carbonate rocks and consists of skeletal and non-skeletal grains (Figure 16 and Figure 17). Crystalline carbonate on the other hand its depositional texture is not recognizable because it was obliterated by diagenesis process. In our samples, we observed the dolomite rocks are in the form of crystalline carbonate. This is because due to the dolomitization process was occurred during deep burial diagenesis and may alter the texture of the rocks into crystalline form (Figure 18 and Figure 19).

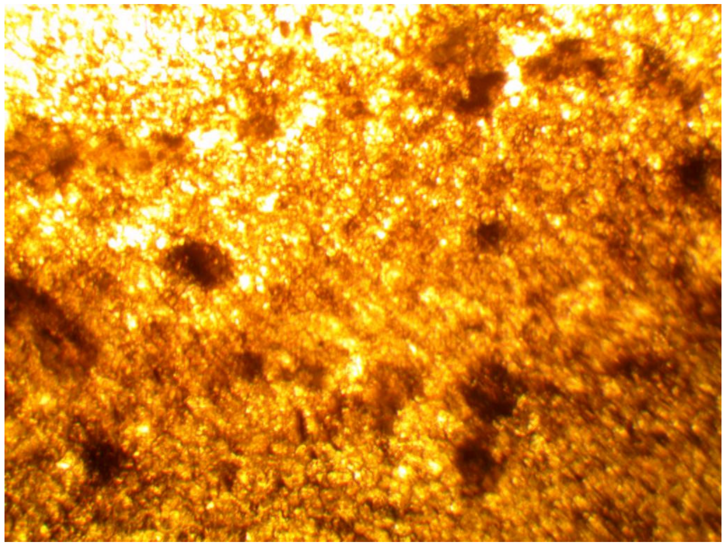


Figure 14. *Sample 7 - Example of observed packestone*

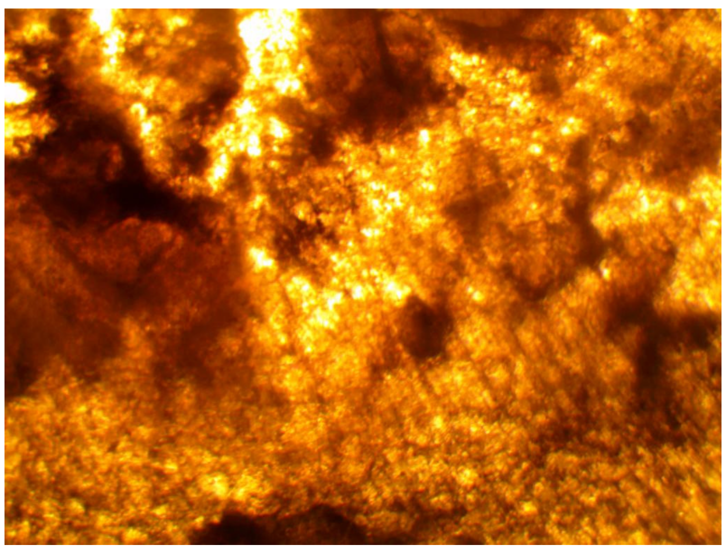


Figure 15. *Sample 13 - Another example of observed packestone*

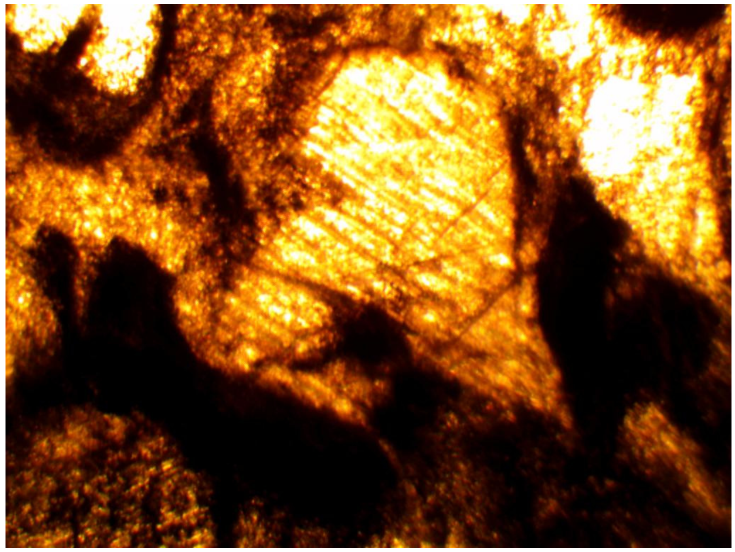


Figure 16. *Sample 1 - Example of observed grainstone*

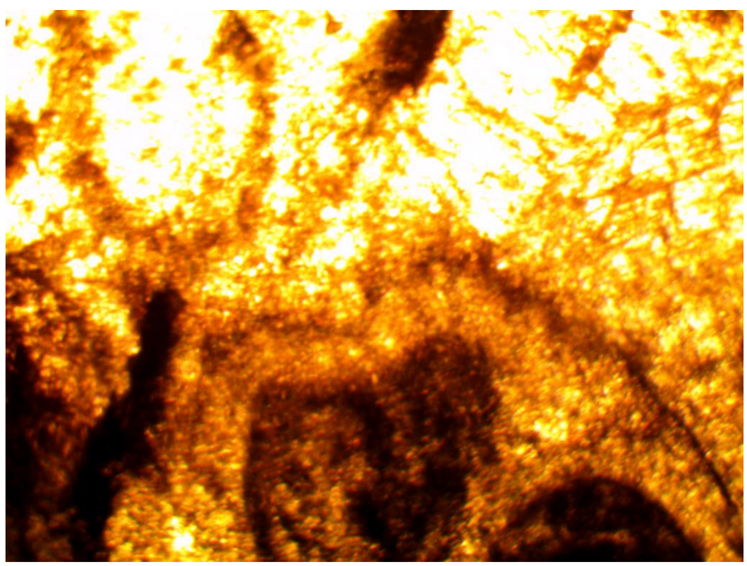


Figure 17. *Sample 18 - Another example of observed*

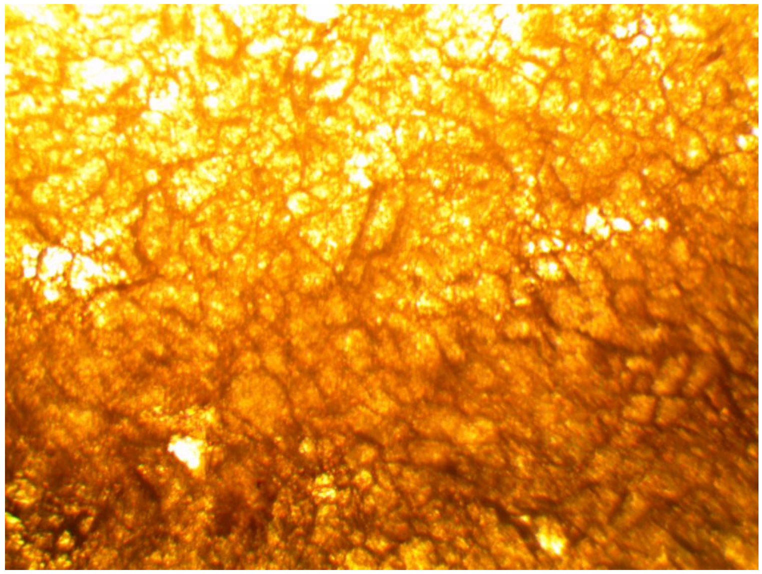


Figure 18. *Sample 5 - Example of observed crystalline*

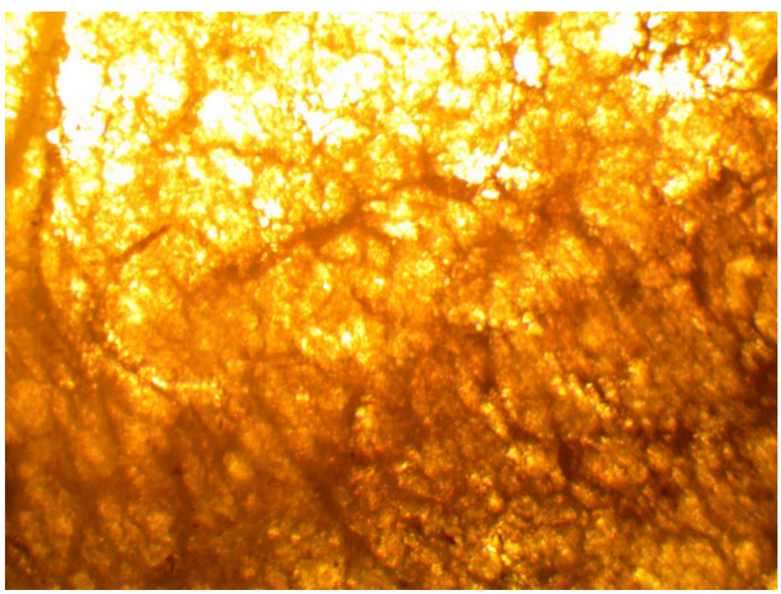


Figure 19. *Sample 6 - Another example of observed crystalline dolomite*

Table 3 – Summary of the type of rock for each sample

Sample	*Type of rocks*
1	Grainstone
2	Crystalline dolomite
3	Crystalline dolomite
4	Crystalline dolomite
5	Crystalline dolomite
6	Crystalline dolomite
7	Packestone
8	Grainstone
9	Crystalline dolomite
10	Grainstone
11	Crystalline dolomite
12	Grainstone
13	Packestone
14	Crystalline dolomite
15	Grainstone
16	Crystalline dolomite
17	Crystalline dolomite
18	Grainstone
19	Crystalline dolomite
20	Crystalline dolomite

For porosity type classification, we tried to apply Choquette and Pray (1970) classification to determine the kind of porosity presence in our carbonate rocks samples. Unfortunately, the porosities of the rocks are too small and not visible through polarized microscope. Hence, the classification of porosity proposed by Choquette and Pray (1970) is not applicable for our samples. We concluded that the dominant 'invisible' porosities of our carbonates are the from the kind of microporosity as classified by Eberli et. al (2003). They grouped the porosity of the carbonate rocks into five categories – interparticle and intercrystalline porosity, microporosity, moldic porosity, intraframe porosity and low porosity carbonates. They define 'microporosity' as micropores with the size of less than 10 micron. The '10 micron microporosities' are too small to be identified using polarized microscope, so Scanning Electron Microscope (SEM) images are needed to identify and locate the microporosities. The abundance of microporosity presence explains the low porosity (less than 6.2 %) and low permeability (less 0.63 mD) that our samples have. The high values of P-wave velocity (4964 m/s to 6818 m/s) and S-wave velocity (2014 m/s to 4258 m/s) also indicated by high amount of microporosity presence in our carbonate rocks from Gunung Rapat.

4.3 SEM IMAGES

Selected 9 of the 20 carbonate samples are analyzed using Scanning Electron Microscope (SEM). The reason we only chose 10 samples is because there were limitations on how many samples each student can analyzed using SEM per month. So, due to short time allocated for the students to complete the project, we only managed to test 10 samples only.

Using classification of microporosity proposed by Rahman et. al. (2011), we tried to analyze and categorize the microporosities in our samples [36]. We observed all 4 kinds of micropores as proposed by Rahman et. al. (2011) – very fine micropores (0.1 - 2 µm), fine micropores (2 - 4 µm), medium micropores (4 - 6 µm) and coarse micropores (6 - 10 µm). For the micrite microtextures, we observed 3 types of micrite microtextures in the carbonate rocks from Gunung Rapat – subrounded micrites, microrhombic and polyhedral micrites and compact anhedral micrites.

Table 4 – Summary of the type of rock, dominant porosity type, and type of micropores and micrite microtextures

Sample	*Type of rock*	*Dominant porosity type*	*Type of micropores*	*Type of micrite microtextures*
4	Packestone	Microporosity	Medium	Subrounded
5	Crystalline dolomite	Microporosity	Very fine	Compact anhedral
6	Crystalline dolomite	Microporosity	Very fine	Compact anhedral

8	Grainstone	Microporosity	Medium	Microrhombic and polyhedral
9	Packestone	Microporosity	Coarse	Microrhombic and polyhedral
14	Crystalline dolomite	Microporosity	Very fine	Subrounded
15	Grainstone	Microporosity	Very fine	Subrounded
16	Packestone	Microporosity	Fine	Subrounded
18	Grainstone	Microporosity	Fine	Microrhombic and polyhedral

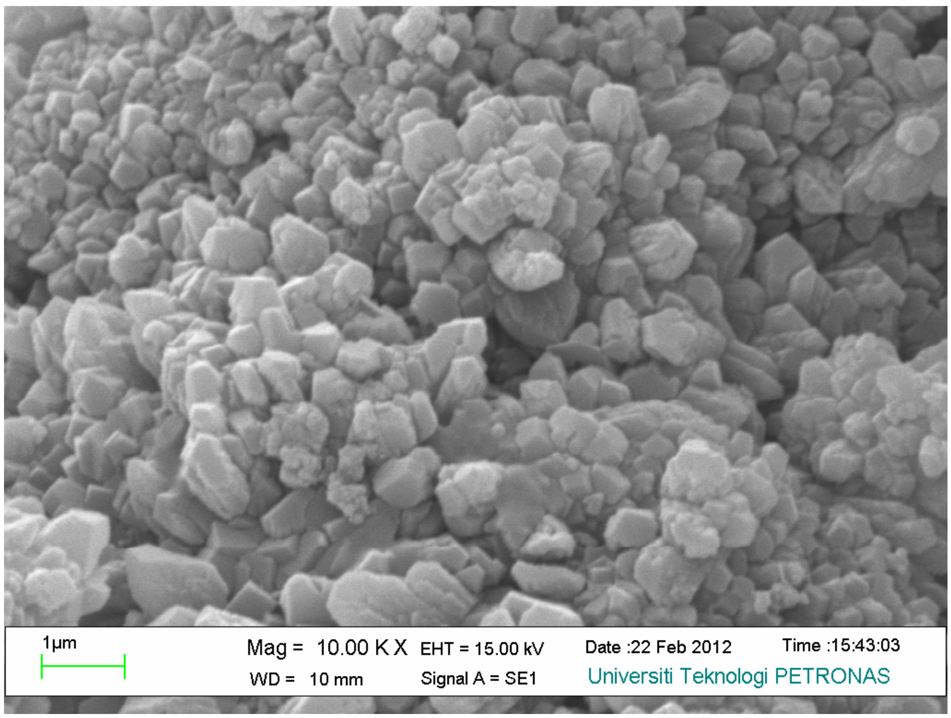


Figure 20. *Sample 15 - Very fine micropores with low porosity and poor interconnection observed in subrounded micrites*

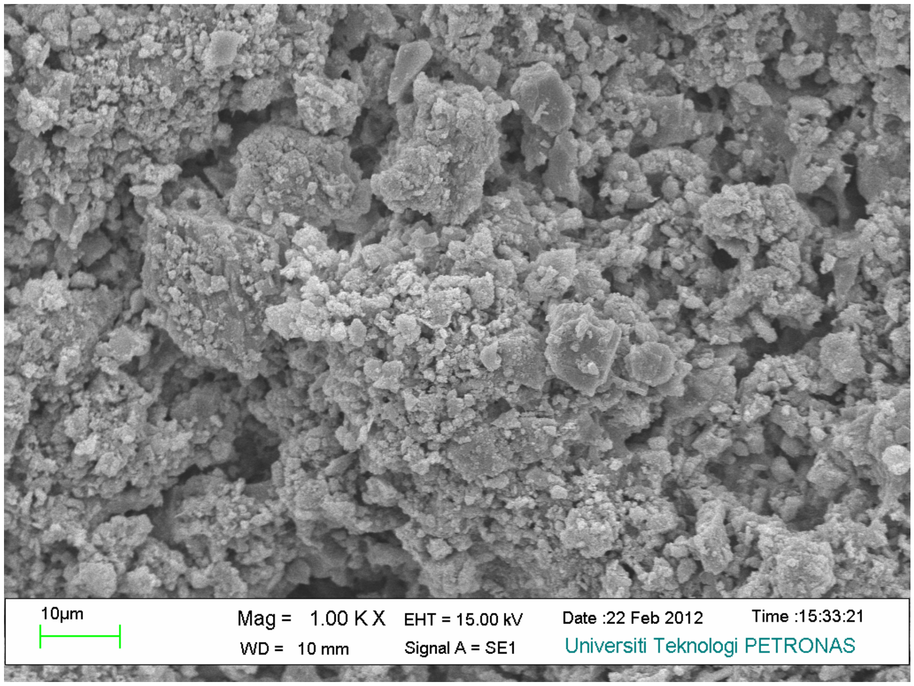


Figure 21. *Sample 16 - Fine micropores with good porosity and moderate interconnection observed in subrounded*

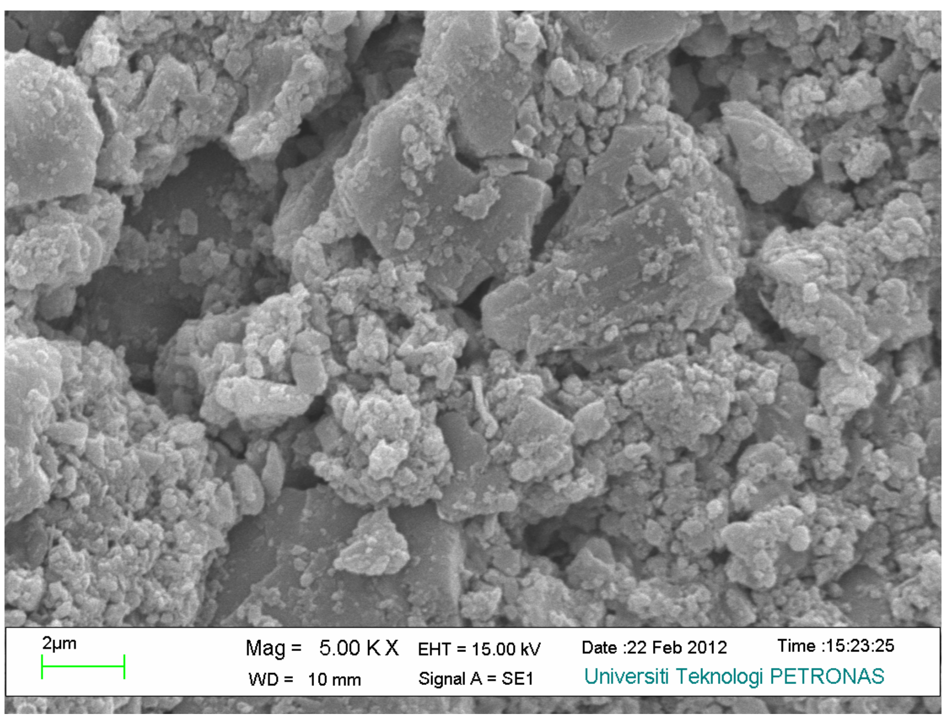


Figure 22. *Sample 18 - Fine micropores with low porosity and poor interconnection observed in microrhombic and polyhedral micrites*

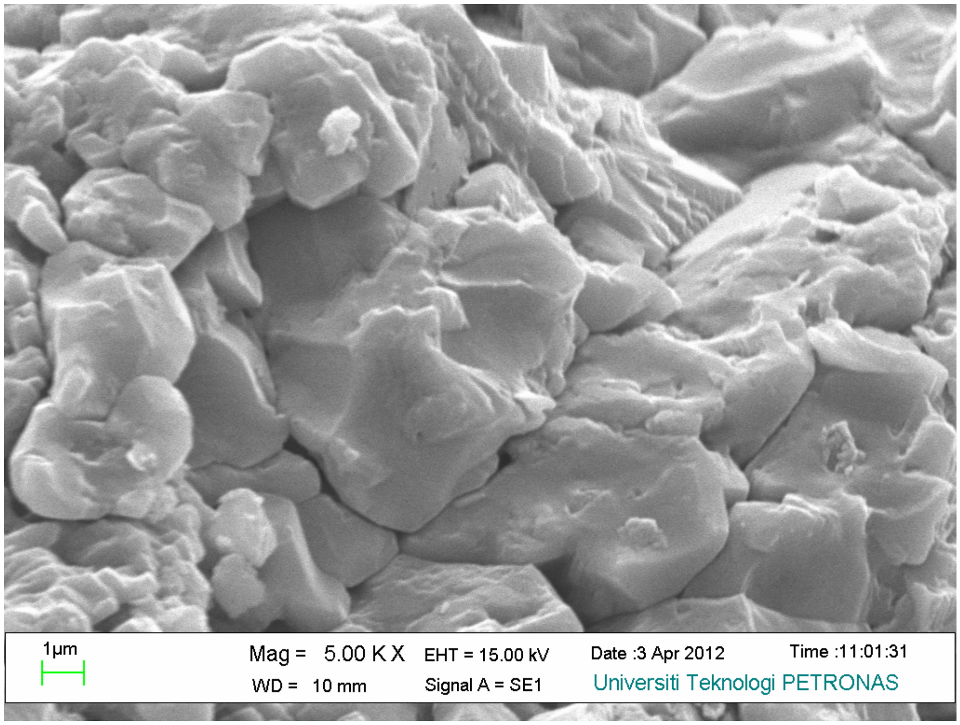


Figure 23. *Sample 6 - Very fine micropores with low porosity and very poor interconnection observed in compact anhedral micrites*

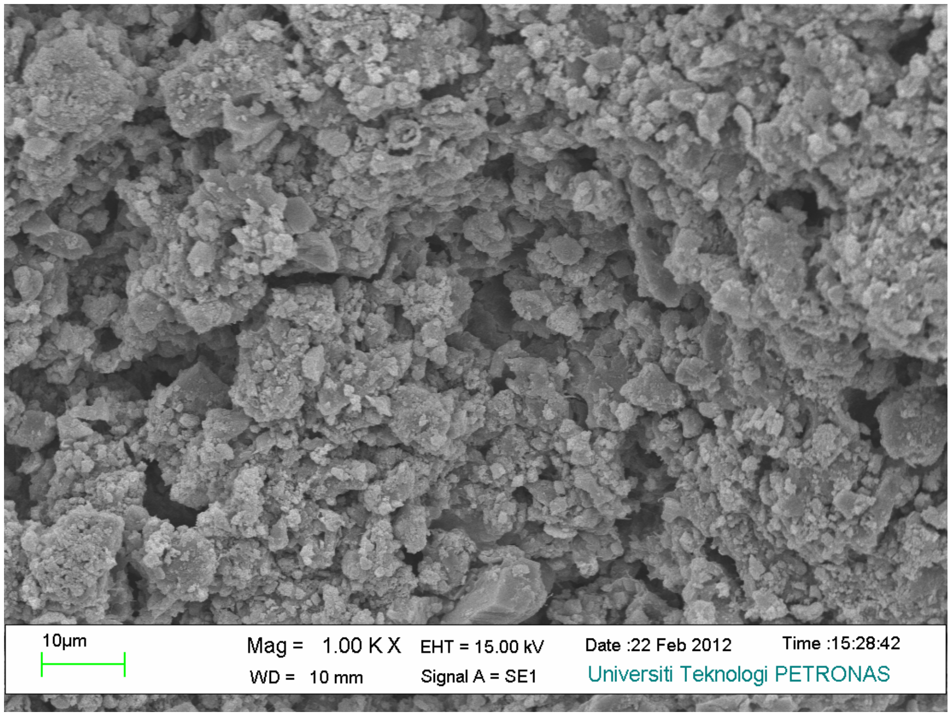


Figure 24. *Sample 4 - Medium micropores with low porosity and poor interconnection observed in subrounded micrites*

From Figure 20 – Figure 23, we observed that microporosity in carbonate rocks not only depends on type of micropores, but also dependent on micrite microtextures. Normally, the rule of thumb is fine micropores will have low porosity, but in the case of carbonates, it is not that easy. Fine micropores can have either low or good porosity depends on their occurrence in certain types of micrite microtextures (Figure 21 and Figure 22). This phenomenon explains the scattered-inverse porosity-P-wave velocity and porosity-S-wave velocity correlations (Figure 8 and Figure 9). Porosity is the main controlling factor in determining the sonic velocity of the rocks but in carbonates from Gunung Rapat, the crystallometry and morphometry of micrite microtextures also equally important in the elastic behavior and resultant sonic velocity. The usual case is, when the porosity amount is high the sonic velocity value will be lower. This is because sounds take shorter time to travel through more porous medium compared to less porous medium. But, the correlations of porosity-sonic velocity for our carbonate rocks are scattered. Sometimes, high porosity rock also can have faster and higher sonic velocity value due to high amount of fine micropores presence in the rock (Figure 21). The sounds are still travelling fast through the rock because of the size of fine micropores is too small to act as a “porous medium”. The sounds will travel smoothly through the fine micropores as it travels through the non-porous rock thus give the high value of sonic velocity.

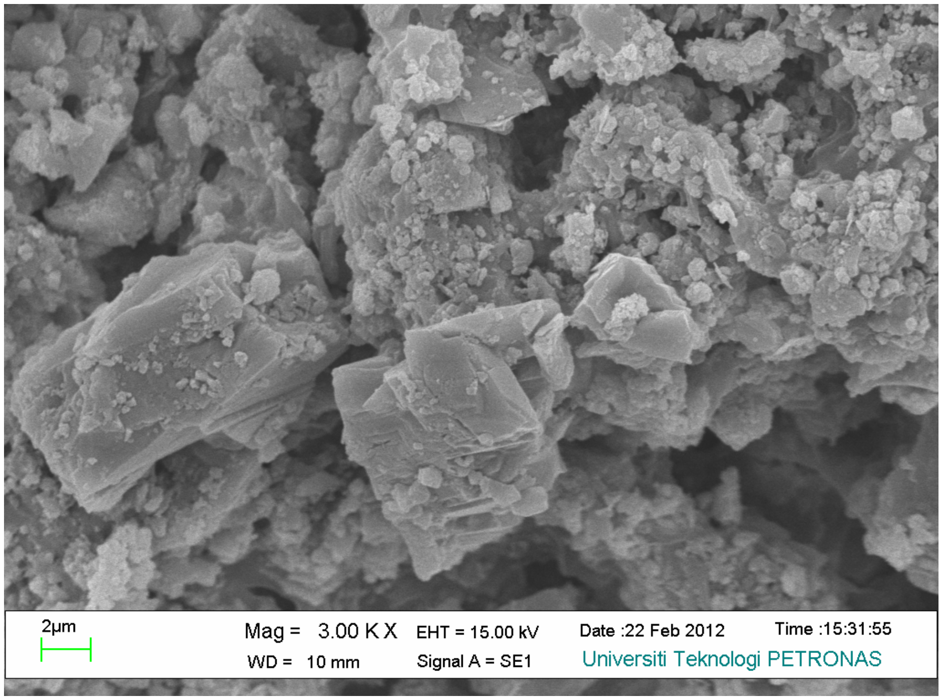


Figure 25. *Sample 8 - Medium micropores with low porosity but moderate interconnection observed in microrhombic and polyhedral*

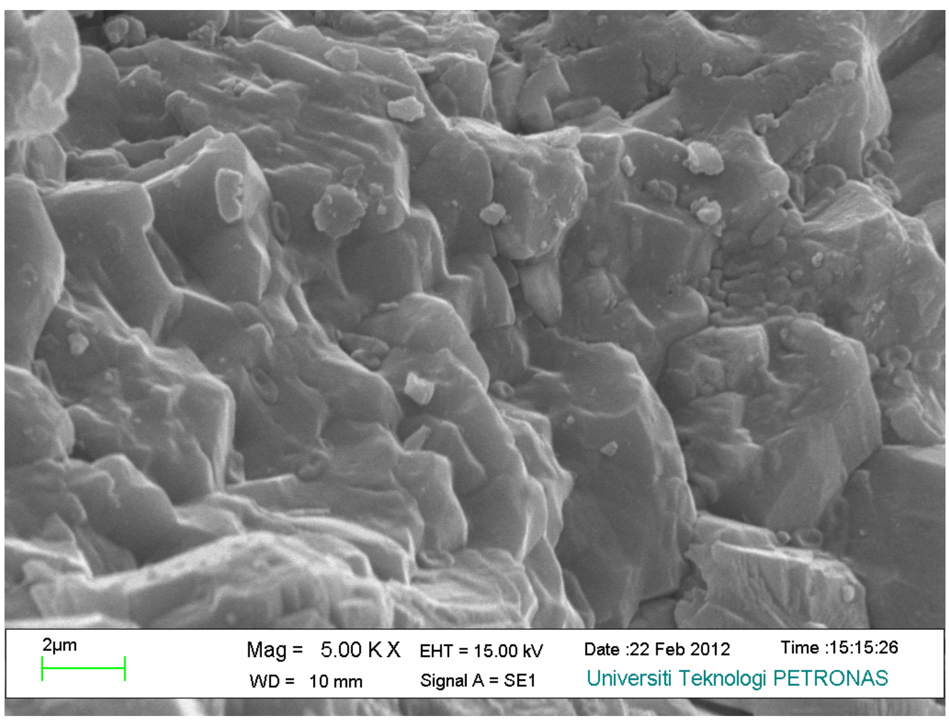


Figure 26. *Sample 5 - Very fine micropores with low porosity and very poor interconnection observed in compact anhedral micrites*

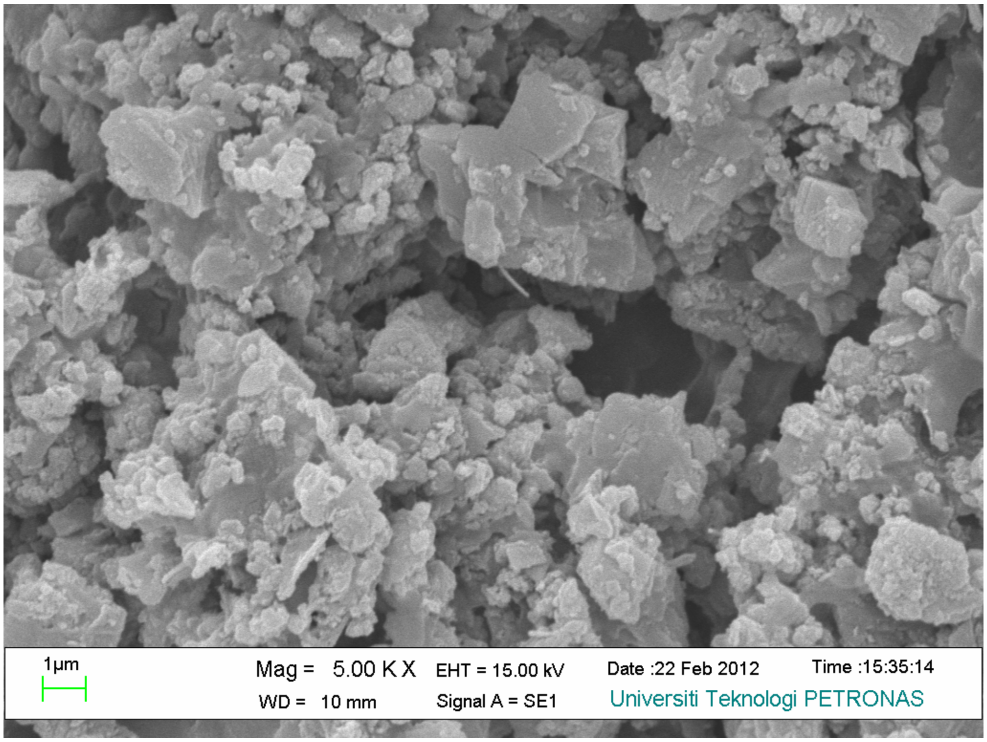


Figure 27. *Sample 9 - Coarse micropores with good porosity and moderate interconnection observed in microrhombic and polyhedral*

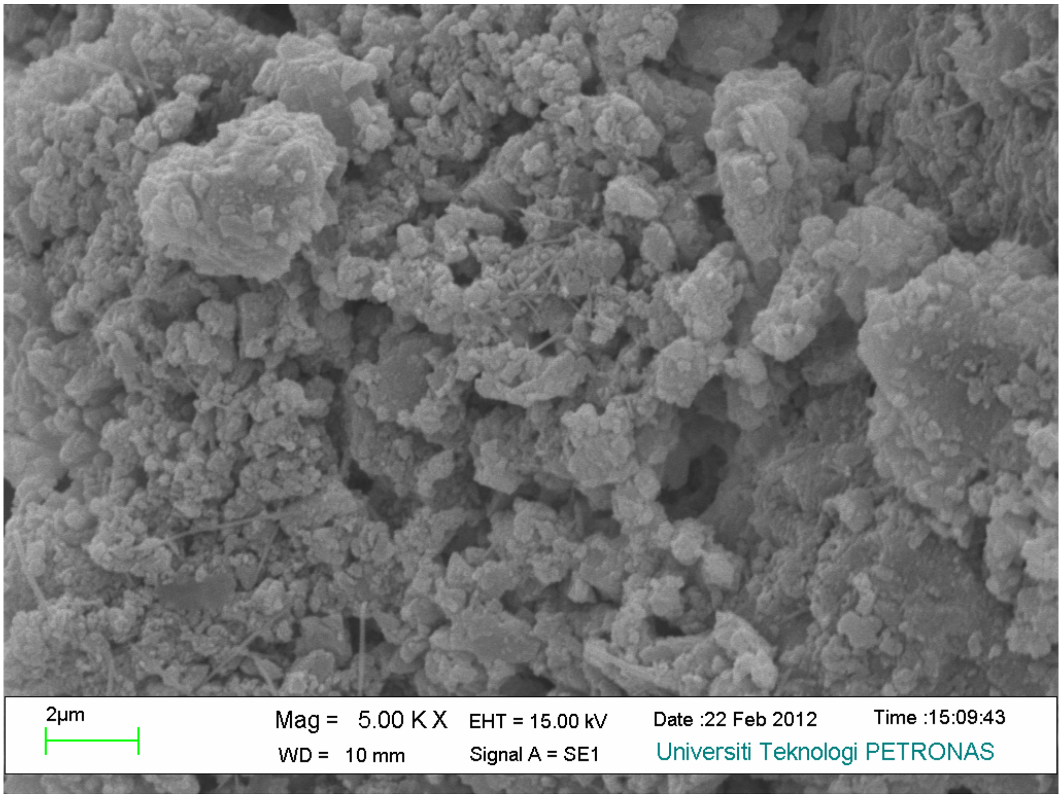


Figure 28. *Sample 14 - Very fine micropores with good porosity but poor interconnection observed in subrounded micrites*

We also observed that permeability of the carbonates rock also governed by the occurrence and distribution of micrite microtextures. The micropores that presence in microrhombic and polyhedral micrites tend to have better connectivity (Figure 25 and Figure 27). Although these micrites sometimes contains lower amount of microporosity, but due to their morphology and textural arrangements, they show good inter-connectivity between the micropores (Figure 25) [37]. The variations in terms of factors controlling the degree on inter-connection between the micropores explain the scattered porosity-permeability correlation. The rule of thumb in porosity-permeability relationship is when the porosity amount contained in the rock is high; the permeability also will have higher value. But in our case, the straight-forward rule is not applicable. The high porosity rock can have either high or low value of permeability and vice versa. The reason is as stated earlier - permeability of the carbonates rock not only governed by porosity but also governed by the occurrence and distribution of micrite microtextures.

The rock can have good porosity value, but because of the occurrence and arrangement of the micrites, its permeability will be lower (Figure 28). Another example is although the porosity amount of the rock is relatively small, but because of occurrence and arrangement of the micrites contribute to good flow, the permeability value of the rock is high (Figure 25). Table 3 summarizes the relative contribution of different microtextures to the fluid flow in carbonate rocks from Gunung Rapat.

Table 5 – The relatives contribution of different pore types of micrite microtextures on fluid flow

Microtexture	*Micropores Present*	*Contribution to fluid flow*
Subrounded micrites	Very fine, Fine, Medium	Poor to Moderate
Microrhombic and polyhedral micrites	Fine, Medium, Coarse	Poor to Moderate
Compact anhedral micrites	Very fine	Very poor

4.4 DOLOMITIZATION'S EFFECT

Using XRD, we will try to find the mineral composition of our samples. Our mineral of interest is the presence of Magnesium (Mg) which indicates the dolomite characteristic of the rocks (Figure 6 and Figure 7). Theoretically, dolomitization can affect the porosity distribution and amount of the carbonates.

During the recrystallization stages late in the diagenesis process of the carbonates, coarser grained dolomite produced thus destroy the sedimentary structures and results in higher porosity. Magnesium (Mg) is a mineral that can replace calcite during process of dolomitization. This geochemical process happens in supratidal sabkha areas where Mg ions from the evaporation of seawater replace calcium Ca ions in calcite, forming the mineral dolomite. The volume of dolomite is less than that of calcite, so the replacement of calcite by dolomite in a rock increases the pore space in the rock by 13% and forms an important reservoir rock [38]. Porosity created by the process of dolomitization is a secondary porosity type.

But in our carbonate samples, we did not observed any effect that dolomitization have either in increasing our decreasing the porosity and permeability. The dolomites in our samples have variations from very low porosity to low porosity (Figure 8, Figure 9, Figure 10, Figure 11 and Figure 13). Contradict to what happen for dolomites, we did not see any variations in the value of porosity and permeability for the limestones. For the limestones, we found that most of the samples are having low porosity and permeability value. The same observation also found in dolomite-sonic velocity relationship. The dolomites also have wide range of sonic velocity from low value to high value of sonic velocity (Figure 8, Figure 9, Figure 10 and Figure 11). Same thing observed in limestones where majority of the samples is not having variations in sonic velocity value; in fact, most of them ara having high sonic velocity value. So, based on our observations, we concluded that dolomite alone cannot be an indicator for porosity, permeability and sonic velocity.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

As a conclusion, objectives for this final year project had been achieved. We managed to establish the correlations of rock properties of the carbonates from Gunung Rapat, Ipoh, Perak. This is a quite achievement as before this; there was a very limited data on rock properties of Paleozoic carbonate in Gunung Rapat as well as their correlations with each other.

From our study, we found a general inverse trend in the correlations of porosity-sonic velocity. However, the correlations show significance scatter and uncertainties. This corroborates that the level of heterogeneity and the various ranges of pore size, structures and types which affect the sonic velocity of the carbonates. We observed that sonic velocity of the carbonate rocks not only influenced by the amount of porosity, but also by the crystallometry and morphometry of micrite microtextures.

The similar observation of inverse and scattered trend also spotted in the correlations of permeability-sonic velocity. However, the correlations are much poorer and have larger uncertainties. This is because; the permeability also affected by the connectivity and effectiveness of the pore space other than pore size, structures and types.

For the relationship between porosity and permeability, we get the result similar from the expected result. Like normal porosity-permeability correlations, we observe the direct trend in the correlation. Even though there is scatter in the correlations, it is understandable because of the grains and pore of the carbonates are usually distributed. We also observed the similar thing where the scatter in the correlation is due to the influenced of the crystallometry and morphometry of micrite microtextures in the flow of the fluid.

In our research on dolomitization's influence on rock physical properties (porosity, permeability and sonic velocity), we did not found any relationship between dolomite with the increase or decrease of values of porosity, permeability and sonic velocity. Our data suggest that changes of this dolomitization process in carbonate rocks have no major influence in rock physical properties.

Lastly, we would like to recommend for future more samples are taken in order to get better results and clearer trends. 20 carbonate samples and 9 SEM images are clearly not enough.

Details analysis also should conducted at several properties in order to understand more on sonic velocity of carbonates as suggested by Anselmetti et al (1993) – the effect of mechanical compaction, burial depth and age of the sediment, effective pressure, depositional lithology, mineralogy, porosity and pore types and density [7]. We also would like to recommend details analysis on the macroporosity and microporosity of the carbonates in order to get better correlations of porosity-sonic velocity and permeability-sonic velocity and porosity-permeability relationships.

For porosity-sonic velocity correlation, Baechle et al. (2006) proved that using microporosity instead of total porosity results in a significant better correlation. The macroporosity displays poor correlation to the P-wave velocity. Using quantitative calculated microporosity instead of total porosity, the velocity uncertainty is significantly reduced. The correlation coefficient increases from 0.67 to 0.86 [8].

For better porosity-permeability correlation, Md Habibur Rahman et al. (2011) suggested that by using quantitative calculated macroporosity from digital images of thin sections, instead of total porosity, improves the correlation coefficient between porosity and permeability from 0.492 to 0.577 [31].

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